

Study of Provenance and Mineralogical Alteration of the Nagaur Sandstones at Shri Balaji Area, Northwestern India: Insights from Integrated Petrography, XRD and XRF analyses

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ABSTRACT

Introduction

Siliciclastic sedimentary rocks preserve a composite record of the geological evolution of their source regions and depositional basins. Their mineralogical and geochemical compositions are controlled by multiple interacting factors, including the lithological character of the source terrain, intensity of pre-depositional alteration, physical erosion, sediment transport and sorting, depositional processes, and subsequent diagenetic modification. Consequently, the composition of a sandstone reflects the combined influence of provenance, sedimentary processes, and post-depositional alteration rather than a single controlling factor. Evaluation of sandstone composition therefore requires an integrated approach in which petrographic, mineralogical, and geochemical characteristics are considered together. Framework-grain assemblages provide important information on the nature of source rocks and sediment provenance, whereas bulk mineralogical and elemental compositions provide complementary constraints on compositional maturity, mineral alteration, and source-rock characteristics (Dickinson et al., 1983; Suttner and Dutta, 1986).

Petrographic analysis provides a fundamental basis for investigating sandstone composition and provenance because it enables direct characterization of framework grains, matrix, cement, and textural relationships. The relative proportions and preservation of quartz, feldspar, and lithic fragments provide important information concerning source-rock composition, sediment maturity, transport history, and sedimentary reworking. Optical characteristics such as feldspar twinning, quartz extinction behaviour, grain shape, sorting, grain contacts, and the occurrence of ferruginous and argillaceous material further assist in distinguishing detrital framework components from secondary phases. Modal framework-grain data can subsequently be evaluated using ternary diagrams such as Q–F–L, which provide a widely used framework for relating sandstone composition to provenance and source-rock characteristics (Dickinson et al., 1983).

Bulk mineralogical analysis provides an important complement to petrographic observations, particularly for identifying fine-grained and clay-rich components that may be difficult to characterize reliably using optical microscopy. X-ray diffraction (XRD) permits identification of crystalline phases within the sandstone and provides information on the relative abundance of quartz, feldspar, clay minerals, and minor accessory phases. Variations in clay-mineral assemblages and feldspar abundance can provide useful evidence for differences in mineral preservation, alteration, and sediment composition. However, clay minerals may represent detrital, authigenic, or diagenetically modified components; therefore, their occurrence should be interpreted in conjunction with petrographic and geochemical observations rather than as an isolated indicator of weathering intensity.

Whole-rock X-ray fluorescence (XRF) geochemistry provides a complementary perspective by quantifying major-element concentrations and allowing variations in bulk-rock composition to be examined systematically. Major elements such as SiO₂, Al₂O₃, Fe₂O₃, K₂O, CaO, MgO, P₂O₅, and TiO₂ are associated with different mineralogical components and can therefore help identify compositional differences among

sandstone samples. High SiO_2 contents may reflect quartz enrichment and compositional maturity, whereas variations in Al_2O_3 , K_2O , Fe_2O_3 , MgO , and TiO_2 may partly reflect differences in feldspar, clay-mineral, and accessory-mineral contributions. Nevertheless, whole-rock geochemistry represents the integrated composition of the sediment and may be influenced by provenance, sedimentary sorting, mineral concentration, recycling, and diagenetic alteration. Accordingly, XRF data are most effectively interpreted in combination with petrographic and XRD observations.

The Marwar Supergroup of northwestern India represents an important Neoproterozoic–Cambrian sedimentary succession for investigating the evolution of sediment supply, depositional systems, and basin development. The succession comprises siliciclastic, carbonate, and subordinate evaporitic deposits and is conventionally subdivided into the Jodhpur, Bilara, and Nagaur groups. Regional studies have demonstrated significant temporal and spatial variations in the provenance of sediments within the Marwar Supergroup, reflecting changes in source contribution during the evolution of the basin (George and Ray, 2017). These variations make the Marwar succession an important geological archive for examining relationships between source-region evolution, sediment dispersal, and basin development.

The Shri Balaji area of Nagaur District provides an appropriate local setting for investigating the composition and provenance of the Nagaur sandstones. The exposed succession includes siliciclastic rocks of the Nagaur group and provides an opportunity to examine the characteristics of sandstone deposited during the later stages of Marwar basin evolution. Variations in sandstone colour, grain size, framework composition, and associated argillaceous material observed within the study area indicate compositional heterogeneity that requires evaluation through integrated petrographic and geochemical approaches. The local occurrence of sandstone and associated sedimentary lithologies therefore provides an opportunity to investigate variations in detrital input, mineralogical preservation, sedimentary modification, and post-depositional alteration at a relatively local scale.

The provenance of the Nagaur sandstones is particularly significant because the regional Precambrian geological framework surrounding the Marwar Basin contains diverse felsic igneous, metamorphic, and metasedimentary terrains that could have contributed detritus to the basin. The Malani Igneous Suite constitutes an important felsic igneous component of the regional geological framework, while older crystalline and metasedimentary rocks associated with the Aravalli–Delhi domains represent additional potential source terrains. However, the occurrence of quartz and feldspar in sandstone does not, by itself, permit assignment to a geographically specific source. Regional provenance investigations have demonstrated that sediment contributions to the Marwar Supergroup varied between stratigraphic intervals and that individual source regions did not necessarily contribute uniformly throughout basin evolution (George and Ray, 2017). Therefore, provenance interpretation of the Shri Balaji sandstones requires integration of framework-grain composition, bulk mineralogy, whole-rock chemistry, and regional geological relationships rather than reliance on a single mineralogical characteristic.

The chemical and mineralogical characteristics of sandstone may additionally preserve evidence of alteration experienced by detrital material before, during, or after deposition. Feldspar is particularly susceptible to chemical alteration and may be progressively transformed into clay-mineral phases under suitable conditions. Consequently, variations in feldspar preservation, clay-mineral abundance, and major-element composition can provide qualitative constraints on the extent of mineralogical alteration experienced by the sediment. In the present study, these characteristics are evaluated through the combined interpretation of petrographic observations, XRD mineralogy, and XRF geochemistry. Such an integrated approach is particularly important because mineralogical and chemical signatures may reflect multiple processes, including source-rock composition, sedimentary sorting and recycling, chemical alteration, and diagenesis.

Interpretation of sandstone weathering signatures requires particular caution because the observed mineralogical and geochemical composition represents the integrated product of several geological processes. Source-rock heterogeneity, selective removal or concentration of minerals during transport, sediment recycling, differential preservation of unstable grains, and post-depositional alteration may all

modify the original weathering signal. Clay minerals, for example, may have either detrital or authigenic origins, while the preservation of feldspar may reflect both source-rock composition and the degree of subsequent alteration. Similarly, enrichment in quartz may result from sedimentary maturation and recycling in addition to source-rock characteristics. Therefore, the present study treats mineralogical and major-element variations as an integrated provenance–alteration signal rather than attributing individual mineralogical or geochemical characteristics exclusively to a single process.

Despite the regional importance of the Marwar Supergroup, detailed integrated studies combining sandstone petrography, modal framework-grain analysis, bulk mineralogy, and major-element geochemistry remain comparatively limited for the Shri Balaji sector. Existing regional provenance studies have provided important constraints on the changing sediment sources of the Marwar basin, but the relationships among framework composition, feldspar preservation, clay-mineral assemblages, and major-element geochemistry at the local scale remain insufficiently documented. In particular, distinguishing provenance-related compositional variability from mineralogical alteration, sedimentary modification, and diagenetic effects is essential for developing a robust interpretation of the Nagaur sandstones exposed in the study area.

Accordingly, the present study employs an integrated petrographic, mineralogical, and geochemical approach to investigate the Nagaur Sandstones of the Shri Balaji area, Nagaur District, Rajasthan.

Geological Setting

The Marwar Supergroup constitutes a major Neoproterozoic–early Cambrian sedimentary succession of northwestern India and is extensively exposed across western and northwestern Rajasthan. The succession occupies a broad intracratonic basin developed above a heterogeneous Precambrian basement and is regionally associated with the Aravalli Orogenic Belt to the east. The Marwar sedimentary succession rests unconformably upon older crystalline and metasedimentary basement rocks, including the Malani Igneous Suite, Erinpura Granite, and rocks belonging to the Delhi, Sirohi, and Punagarh groups. This heterogeneous Precambrian geological framework is of particular significance for provenance studies because several of these lithological domains constitute potential sources of detrital material supplied to the Marwar Basin (GSI, 2001; George and Ray, 2017).

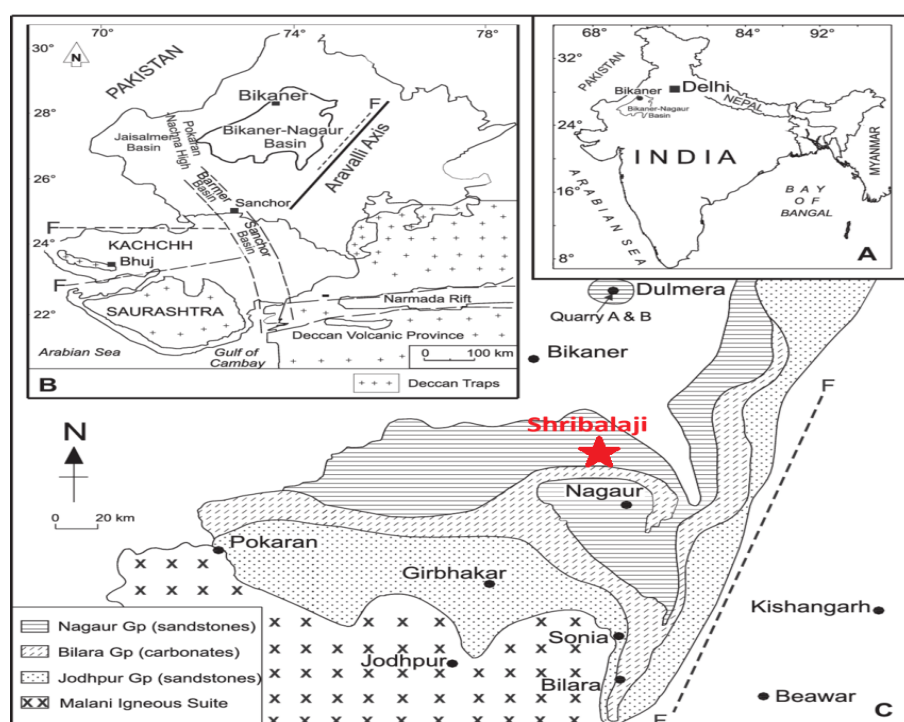


Fig. 1: Location and regional geological map of the study area. (A) Outline map of India showing the outcrop distribution of the Marwar Supergroup within the Bikaner–Nagaur Basin. (B) Regional structural elements of western Rajasthan and the basin boundary. (C) Geological map of the Marwar

Supergroup in west-central Rajasthan. The red star indicates the location of the Shribalaji study area. Modified after Misra et al. (1993), Shrivastava (1971), and Pareek (1984).

The Marwar Supergroup is conventionally subdivided into three principal lithostratigraphic groups: the Jodhpur Group, Bilara Group, and Nagaur Group. These units record major changes in depositional conditions through the evolution of the basin. The Jodhpur Group is predominantly siliciclastic and includes sandstone, shale, siltstone, and associated sedimentary rocks. It is overlain by the Bilara Group, which is dominated by carbonate lithologies, including dolomite and limestone. The uppermost Nagaur Group represents a return to predominantly siliciclastic sedimentation and includes sandstone, siltstone, claystone, and locally conglomeratic and evaporitic deposits. This stratigraphic organization records a broad transition from siliciclastic sedimentation through carbonate-dominated deposition to renewed siliciclastic sedimentation during the later evolution of the Marwar Basin (GSI, 2001; George and Ray, 2017). The Precambrian basement exposed around the basin comprises lithological units of contrasting composition, including felsic igneous rocks, granitoids, quartzite, schist, phyllite, and other metamorphic rocks. Such lithological diversity provides an important regional framework for evaluating variations in the mineralogical and geochemical composition of the Marwar siliciclastic succession (GSI, 2001). The generalized stratigraphic relationships are summarized in **Table 1**.

Table 1: Regional Stratigraphy of the Marwar Supergroup (GSI, 2001)

Age	Supergroup/ Group	Formation	Rock Type
Recent to Sub-Recent	Quaternary	-	Aeolian sand, kankar, clay, calc sandstone
Lower Eocene (60 Ma)	-	Jogira Fuller's Earth	Calcareous shale, siltstone, marl, limestone, sandy limestone
-	Hanseran / Evaporite Group (equivalent to Bilara Group)	-	Gypsiferous limestone & claystone, clay, halite containing potash minerals, anhydrite, dolomite, magnesite & glauconite
Lower Cambrian (570 Ma)	Marwar Supergroup > Nagaur Group	Tunklian Sandstone	Red claystone, siltstone, calcareous clay & gritty to pebbly sandstone
-	-	Nagaur Sandstone	Red sandstone, siltstone, claystone, conglomerate
-	Bilara Group	Pondlo Dolomite	Dolomite, dolomitic limestone
-	-	Gotan Limestone	Limestone, dolomite, chert and cherty dolomite
-	-	Dhanapa Dolomite	Stromatolitic limestone/dolomite, cherty dolomite, dolomitic limestone
-	Jodhpur Group	Girbhakar Sandstone	Siltstone, shale & sandstone
-	-	Sonia Sandstone	Shale, sandstone, banded chert & carbonate
Late Proterozoic (745 ± 10 Ma)	Malani Igneous Suite	-	Rhyolite and granite
Late Proterozoic (800 Ma)	Punagarh Group	-	Shale, phyllite, mica schist & quartzite with metavolcanics
-	Sirohi Group	-	Phyllite, mica schist with intercalated

			quartzite & marble
Late Proterozoic (900 Ma)	Erinpura Granite	-	Gneissic granite, migmatized granite and massive granite
Middle Proterozoic (1600–2000 Ma)	Delhi Supergroup > Ajabgarh Group	-	Crystalline limestone & marble, siliceous limestone, ferruginous quartzite, slate & schist
-	-	Alwar Group	-
-	-	Railo Group / Ras Formation	-

The regional distribution of the Marwar Supergroup, its relationship with the surrounding Precambrian geological framework, and the location of the Shri Balaji study area are illustrated in **Fig. 1**, modified from published geological and regional mapping sources (Misra et al., 1993; Shrivastava, 1971; Pareek, 1984).

Stratigraphy and Geology of the Shri Balaji Study Area

The study area is situated around Shri Balaji in Nagaur District, Rajasthan, where well-developed surface exposures provide an opportunity to examine the stratigraphic relationship between the carbonate-dominated Bilara Group and the overlying siliciclastic Nagaur Group. The local succession exposed in the study area begins with massive to thickly bedded, sucrosic dolomite assigned to the Pondlo Dolomite of the Bilara Group. These carbonate rocks are overlain by red to buff, medium- to coarse-grained sandstones belonging to the Nagaur Formation (GSI, 2001; George and Ray, 2017).

The contact between the underlying dolomitic succession and the overlying sandstone marks a pronounced lithological change from carbonate-dominated to siliciclastic sedimentation. The Nagaur Sandstones exposed at the Shri Balaji area display prominent bedding and locally developed cross-bedding, together with variations in grain size and colour from reddish to buff tones. Argillaceous horizons occur locally in association with the sandstone beds, producing vertical lithological variations within the exposed succession. These characteristics provide an appropriate stratigraphic framework for investigating variations in detrital composition and mineralogical characteristics within the Nagaur sandstone.

The Nagaur Sandstone constitutes the principal siliciclastic unit investigated in the present study. Field observations and sample descriptions indicate variations in lithology from relatively coarse-grained, quartz-rich sandstone to sandstone associated with argillaceous material. Individual beds show differences in colour, grain size, induration, and textural characteristics. The studied sandstone horizons include bedded sandstone with associated shale, white to light-coloured coarse-grained sandstone, sandstone interbedded with reddish argillaceous material, yellowish indurated sandstone, and alternating red and white sandstone beds. These lithological variations are represented by the sampling localities used for petrographic, XRD, and XRF investigations.

The stratigraphic position of the studied sandstone above the Pondlo Dolomite is particularly relevant to the interpretation of the Nagaur succession. The change from carbonate to siliciclastic deposition indicates a major modification in sediment supply and depositional conditions within the local succession. However, the specific depositional sub-environment of the studied sandstone cannot be established solely from the present petrographic and geochemical datasets and therefore is considered together with field-based sedimentological observations.

At the regional scale, the Nagaur group overlies the Bilara group and includes the Nagaur sandstone followed upward by the Tunklian Sandstone. The Bilara Group includes the Pondlo Dolomite, Gotan Limestone, and Dhanapa Dolomite. This stratigraphic relationship places the Shri Balaji sandstone succession within the upper part of the Marwar Supergroup and provides the regional geological context for evaluating its provenance and mineralogical evolution.

MATERIALS AND METHODS

Field Sampling and Sample Preparation

Field investigations were conducted at the Shri Balaji area of Nagaur District, Rajasthan, with particular emphasis on the sandstone-bearing succession of the Nagaur Formation. Representative sandstone samples were collected from well-exposed outcrops exhibiting variations in lithology, colour, grain size, bedding characteristics, and associated argillaceous material. The sampling localities were selected to capture the compositional variability observed within the exposed sandstone succession. The geographic coordinates and field characteristics of the individual sampling sites are summarized in **Table 2**.

Table 2. Spatial distribution and lithological characteristics of the studied samples.

Sample ID	Latitudes (N)	Longitudes (E)	Elevation (m)	Lithological characteristics
SBL-1	27°24'40"	73°31'57"	300	Bedded sandstone and shale, alternating sequences
SBL-2	27°24'38"	73°31'59"	290	White, coarse-grained siliciclastic sandstone
SBL-3	27°24'36"	73°32'01"	300	Sandstone interbedded with argillaceous red shale
SBL-4	27°24'37"	73°32'04"	300	Yellow, heavily indurated, coarse-grained sandstone
SBL-5	27°24'39"	73°32'06"	300	Alternating red and white sandstone beds
SBLB-1	27°22'56"	73°31'40"	320	Quartzite from isolated topographic high
SBLB-2	27°22'52"	73°31'45"	320	Quartzite exhibiting distinct dendritic textures
SBLB-3	27°22'54"	73°31'40"	320	Massive quartzite, lithologically akin to SBLB-2
SBLB-4	27°22'52"	73°31'38"	300	Ferruginous red shale
SBLB-5	27°22'53"	73°31'50"	310	Blocky, indurated lithofacies
SBLB-6	27°22'54"	73°31'51"	305	Dark gray, thinly bedded lithology
SBLB-7	27°22'56"	73°31'41"	300	Blocky, dark brown-gray lithology
SBLB-8	27°22'56"	73°32'02"	300	Dark gray facies with deformed laminations
SBLB-9	27°22'54"	73°31'42"	310	White lithology with secondary blue dendritic patches
SBLB-10	27°22'57"	73°32'22"	300	Blocky, dark gray, thinly laminated facies
SBLB-11	27°22'52"	73°31'38"	300	Argillaceous white shale

Representative fresh portions of the sandstone samples were selected for laboratory investigation after removing visibly weathered surfaces. The samples were cleaned to eliminate loose surface material and subsequently prepared for petrographic, mineralogical, and geochemical analyses. Separate portions of the representative samples were used for thin-section preparation, X-ray diffraction (XRD), and whole-rock X-ray fluorescence (XRF) analysis. The analytical datasets were subsequently integrated to evaluate variations in framework composition, mineral assemblages, and major-element chemistry.

For petrographic investigation, representative sandstone fragments were cut and prepared as standard polished thin sections. The sections were examined under transmitted light using plane-polarized and cross-polarized illumination. Particular attention was given to the identification and characterization of quartz,

feldspar, lithic components, matrix, and secondary mineral phases, together with grain size, sorting, roundness, grain contacts, and textural relationships.

Petrography and Modal Analysis

Petrographic analysis was undertaken to characterize the framework mineralogy, textural maturity, and compositional variability of the Nagaur Sandstones. Thin sections were examined using a polarizing petrographic microscope under plane-polarized light (PPL) and crossed-polarized light (XPL). Individual mineral phases were identified on the basis of their optical properties, including colour, relief, cleavage, twinning, extinction behaviour, interference colours, and crystal morphology.

Particular emphasis was placed on distinguishing the principal framework components, namely quartz, feldspar, and lithic fragments, as well as matrix and secondary ferruginous or argillaceous material. Quartz grains were further examined for monocrystalline and polycrystalline character and for variations in extinction behaviour. Feldspar grains were identified using their characteristic cleavage, twinning, alteration features, and optical properties. Textural parameters including grain size, sorting, roundness, grain packing, and grain-to-grain contacts were also recorded to evaluate variations in sediment maturity and depositional modification.

Modal framework-grain proportions were determined using point-counting analysis following the principles of the Gazzi–Dickinson method (Ingersoll et al., 1984). Approximately 200–235 framework grains were counted per thin section, depending on the quality and distribution of identifiable grains. The principal framework categories were quartz (Q), feldspar (F), and lithic fragments (L). The modal percentages were normalized to the total $Q + F + L$ framework population and plotted on a Q–F–L ternary diagram to evaluate the compositional character and broad provenance affinity of the sandstone samples (Dickinson et al., 1983).

The petrographic observations were interpreted together with the XRD and XRF datasets because individual framework minerals may undergo alteration, dissolution, replacement, or diagenetic modification after deposition. Thus, modal composition was treated as one component of the integrated provenance interpretation rather than as an independent indicator of a unique source terrain.

X-Ray Diffraction (XRD) Analysis

Bulk mineralogical characterization was performed using X-ray diffraction (XRD) analysis on representative sandstone samples. The analysis was undertaken to identify the principal crystalline mineral phases and to characterize variations in feldspar and clay-mineral assemblages that may not be readily resolved through optical petrography alone.

Representative portions of the sandstone samples were crushed and powdered prior to XRD analysis. The powdered material was homogenized to obtain a representative analytical fraction and subjected to X-ray diffraction for mineral-phase identification. The resulting diffraction patterns were interpreted by comparison with reference diffraction characteristics of the constituent minerals.

The XRD analysis identified quartz as the dominant mineral phase in all analysed sandstone samples, together with variable proportions of microcline and clay minerals including kaolinite and illite. Minor phases such as hematite, ilmenite, and smectite were also identified in selected samples. The relative mineralogical proportions obtained from the XRD analysis were used to examine variations in quartz abundance, feldspar preservation, and clay-mineral development among the sandstone samples.

The XRD results were interpreted in conjunction with petrographic observations because clay minerals may have either detrital or authigenic origins, while feldspar abundance may reflect both provenance and subsequent mineralogical alteration. Accordingly, variations in clay-mineral assemblages were considered as evidence of mineralogical variability and alteration rather than being interpreted independently as a quantitative measure of paleoweathering intensity.

Whole-Rock X-Ray Fluorescence (XRF) Analysis

Whole-rock major-element geochemical analyses were performed using X-ray fluorescence (XRF) on representative sandstone samples. The analysis was undertaken to characterize the bulk chemical composition of the sandstones and to identify variations associated with their mineralogical and compositional heterogeneity.

Representative powdered sandstone samples were prepared for XRF analysis following standard laboratory procedures. The concentrations of major oxides including SiO₂, Al₂O₃, Fe₂O₃, K₂O, CaO, MgO, P₂O₅, and TiO₂ were determined and expressed as weight percentages (wt.%). The analytical dataset comprises five representative samples, designated SBL-1 to SBL-5.

The XRF dataset is characterized by high SiO₂ concentrations ranging from 76.792 to 93.651 wt.%, whereas Al₂O₃ ranges from 1.708 to 10.973 wt.%, Fe₂O₃ from 0.916 to 5.213 wt.%, and K₂O from 0.263 to 3.308 wt.%. CaO, MgO, P₂O₅, and TiO₂ occur in comparatively lower concentrations and display sample-to-sample variations. These major-element variations were evaluated in relation to the petrographic and XRD-derived mineralogical compositions.

The analytical configuration of the XRF facility covered elements from Mg to U; consequently, Na₂O was not reliably quantified in the available dataset. Therefore, Na₂O-dependent geochemical calculations were not performed in the present study. The XRF results are instead used directly to characterize major-element variability and to evaluate the relationship between bulk-rock chemistry and mineralogical composition.

Integrated Data Analysis and Provenance Interpretation

The petrographic, modal, XRD, and XRF datasets were integrated to develop a comprehensive interpretation of the provenance and mineralogical evolution of the Nagaur Sandstones. Petrographic observations were used to establish the framework-grain composition and textural characteristics of the sandstone, while Q–F–L modal data provided a quantitative representation of the framework-mineral assemblage.

The XRD results were subsequently compared with the petrographic observations to evaluate the preservation and distribution of quartz, feldspar, and clay-mineral phases. Particular attention was given to the relationship between microcline abundance, clay-mineral development, and the observed textural characteristics of individual samples. The XRF data were then evaluated alongside the mineralogical results to determine whether variations in major-element composition correspond to changes in quartz, feldspar, clay-mineral, and ferruginous components.

Provenance interpretation was based primarily on the combined framework-mineral composition, Q–F–L modal distribution, mineral assemblages, and major-element characteristics. The regional Precambrian geological framework surrounding the Marwar Basin was considered as an additional constraint when evaluating potential source lithologies.

Because quartz- and feldspar-rich sandstone compositions may be produced by more than one type of felsic to metamorphic source terrain, the analytical results were not used to assign the sandstone to a single geographically specific source without independent provenance-sensitive evidence.

Variations in feldspar preservation, clay-mineral abundance, ferruginous phases, and bulk-rock chemistry were additionally considered in evaluating mineralogical alteration. Such variations may reflect a combination of source-rock composition, chemical alteration, sedimentary sorting and recycling, and post-depositional modification. Consequently, the provenance and alteration interpretations presented in this study are based on the convergence of multiple datasets rather than on any single mineralogical or geochemical parameter.

RESULTS

Petrographical Characteristics

Optical petrographic examination of the Nagaur Sandstones reveals a quartz-dominated framework assemblage with subordinate feldspar and negligible lithic-fragment contribution. The framework grains are predominantly composed of monocrystalline quartz, which commonly exhibits non-undulatory to weakly undulatory extinction under crossed-polarized light. Quartz grains occur as discrete subangular to subrounded grains and locally display close grain packing and interlocking grain contacts. Variations in grain size, sorting, packing, and matrix content are observed among the analysed samples, indicating differences in the textural maturity of individual sandstone horizons.

Feldspar constitutes the principal subordinate framework component and is represented predominantly by microcline, with minor plagioclase. Microcline is recognized by its characteristic cross-hatched twinning and is locally preserved as relatively fresh detrital grains. Plagioclase is identified by polysynthetic twinning and occurs in minor proportions. The preservation of feldspar within the quartz-rich framework indicates that the sandstone contains a significant crystalline detrital component despite its high degree of quartz enrichment. The sandstone samples exhibit variations from moderately sorted, grain-supported fabrics to comparatively poorly sorted fabrics containing greater amounts of argillaceous material. Grain contacts range from point and long contacts to locally developed concavo-convex contacts, reflecting differences in compaction and post-depositional modification. Ferruginous and argillaceous material occurs within intergranular spaces and locally forms coatings or cement-like concentrations around framework grains. These components contribute to the reddish to buff colour variations observed in hand specimens.

The petrographic characteristics indicate that the studied sandstones are compositionally mature to sub-mature quartz-rich siliciclastics, but their framework composition is not completely uniform. The variable proportions of feldspar and argillaceous material provide evidence for differences in detrital input and/or subsequent sedimentary and post-depositional modification. Representative petrographic characteristics of the studied samples are illustrated in **Fig. 2**.

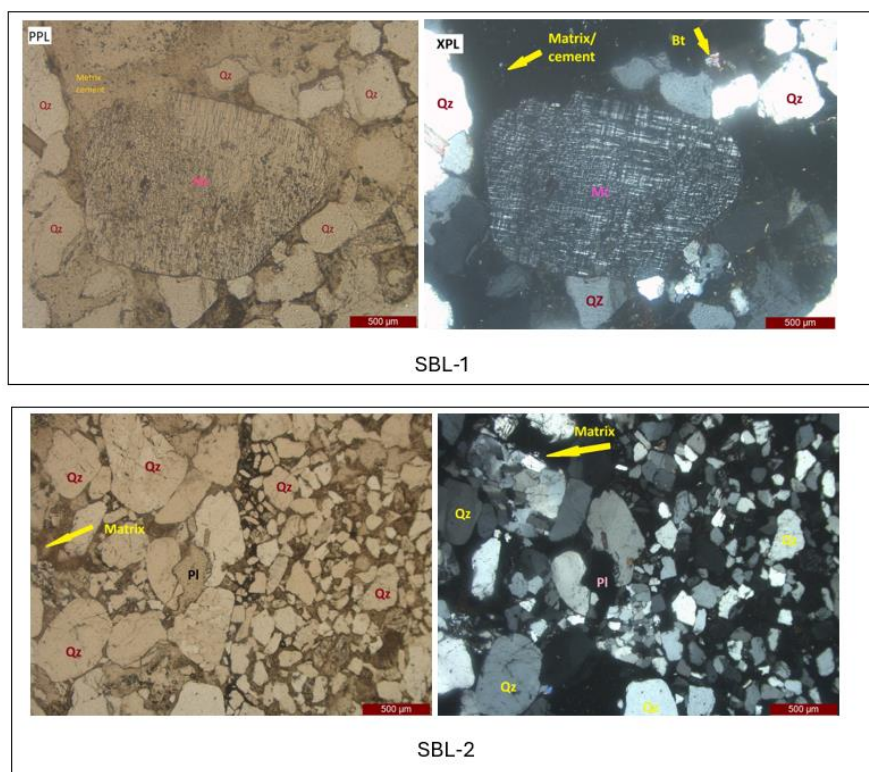
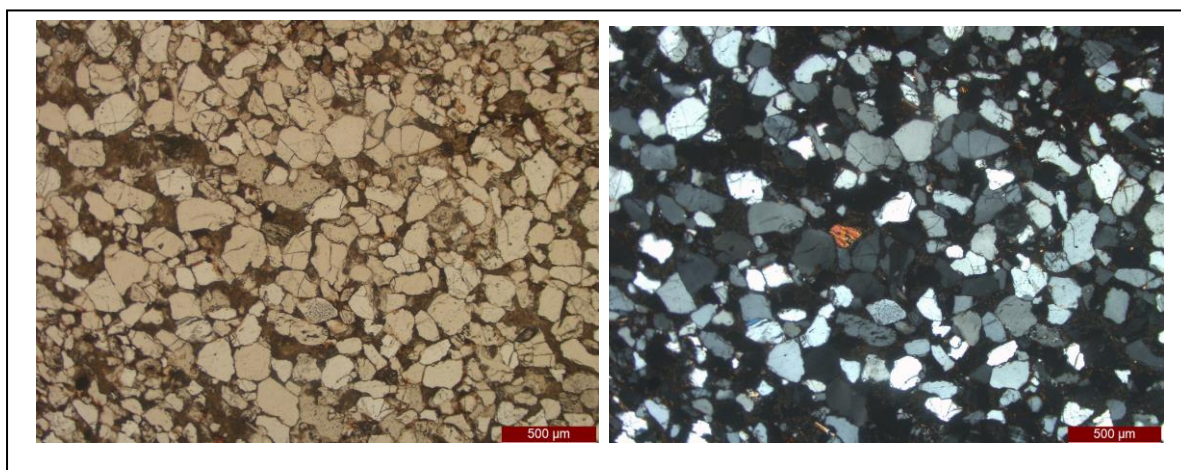
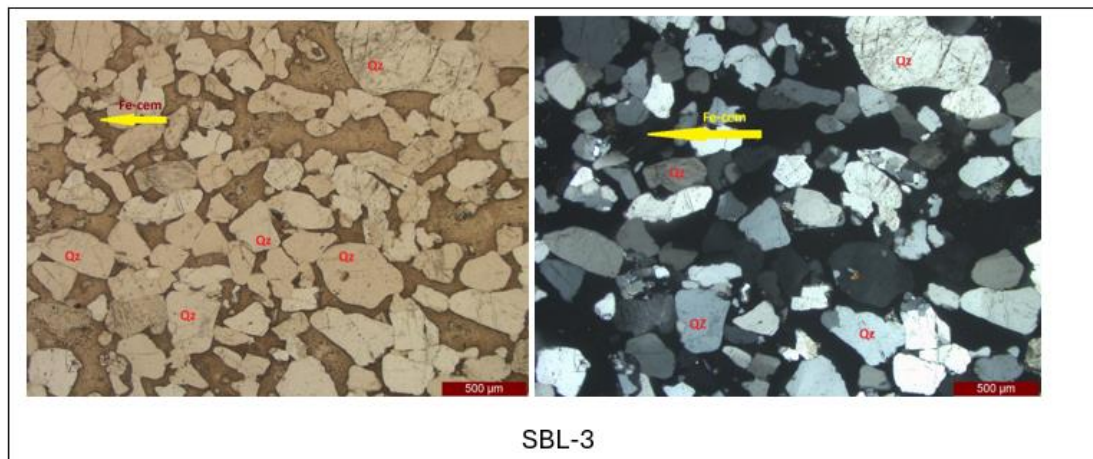


Fig. 2. Representative photomicrographs of the Nagaur sandstones (SBL-1 to SBL-5) under plane-polarized and cross-polarized light.



Modal Q–F–L Composition

Modal framework-grain analysis was performed on samples SBL-1 to SBL-10 using the Q–F–L classification. Quartz constitutes the dominant framework component in all analysed samples, ranging from **70.1% to 93.7%**, whereas feldspar ranges from **6.3% to 29.9%**. Lithic fragments were not recorded in the point-count dataset.

SBL-3 records the lowest quartz proportion (**70.1%**) and the highest feldspar proportion (**29.9%**), followed by SBL-5, which contains **72.4% quartz and 27.6% feldspar**. In contrast, SBL-8 is the most quartz-rich sample, with **93.7% quartz and 6.3% feldspar**, followed by SBL-2 with **92.3% quartz and 7.7% feldspar**. The remaining samples contain intermediate proportions of quartz and feldspar.

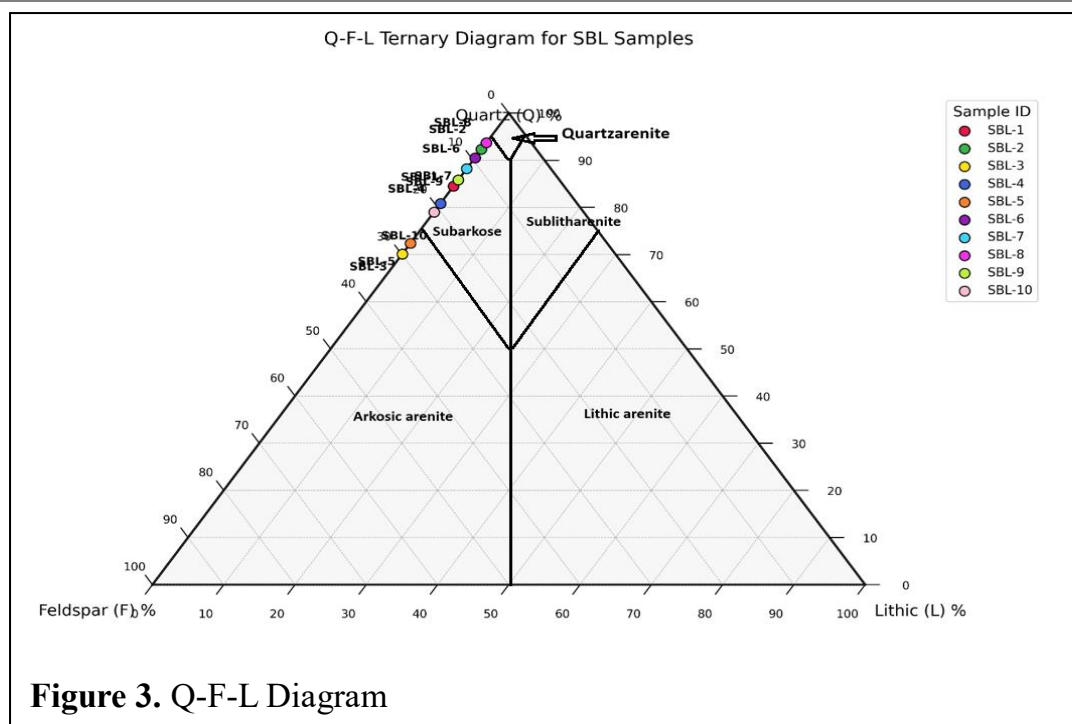


Figure 3. Q-F-L Diagram

The Q–F–L distribution therefore demonstrates a consistently quartz- and feldspar-dominated framework with negligible lithic contribution. The variation in quartz-to-feldspar ratio indicates compositional heterogeneity within the sandstone succession. The Q–F–L modal compositions are plotted on the ternary diagram in **Figure 3**

XRD Mineralogy

X-ray diffraction analysis of samples SBL-1 to SBL-5 confirms quartz as the dominant mineral phase in all analysed sandstone samples. The calculated quartz abundance ranges from **70.1% to 94.5%**. SBL-1 contains the highest quartz abundance at **94.5%**, followed by SBL-2 (**92.3%**) and SBL-4 (**90.8%**). Lower quartz contents occur in SBL-3 (**70.1%**) and SBL-5 (**72.4%**), corresponding to comparatively higher proportions of feldspar and clay minerals.

Microcline is the principal feldspar identified by XRD and occurs in variable proportions. It is absent or below the reported proportion in SBL-2, whereas SBL-1 contains **3.8%**, SBL-3 and SBL-4 each contain **5.9%**, and SBL-5 contains **7.4%** microcline. The occurrence of microcline is consistent with the petrographic identification of K-feldspar and confirms the preservation of feldspathic detritus within the quartz-rich sandstone framework. The clay-mineral assemblage consists primarily of **kaolinite and illite**, with minor smectite in SBL-4 and SBL-5. Kaolinite abundance varies considerably, from **1.4% in SBL-1** to **12.9% in SBL-5**, while illite ranges from **2.9% in SBL-4** to **9.2% in SBL-3**. The combined clay-mineral content is highest in SBL-3 (**21.4%**) and SBL-5 (**19.1%**) and considerably lower in SBL-1 (**1.4%**) and SBL-4 (**3.2%**).

Minor iron-bearing phases are also detected. Hematite occurs in SBL-2, SBL-3, and SBL-5, whereas ilmenite is identified in SBL-3. The occurrence of these phases is consistent with the ferruginous characteristics observed petrographically. However, the XRD data alone do not establish the textural origin or paragenetic timing of these iron-bearing phases. Overall, the XRD results demonstrate systematic sample-to-sample variation in the relative proportions of quartz, microcline, and clay minerals. Samples SBL-3 and SBL-5 are distinguished by relatively lower quartz contents and higher clay-mineral abundances, whereas SBL-1 and SBL-2 are strongly quartz dominated. The complete XRD dataset is presented in **Table 3**, and representative diffraction patterns are shown in **Figure 3**. The numerical XRD results are supported by the analytical dataset in the current manuscript.

Table 3. Quantitative XRD mineralogical composition of the Nagaur Sandstone at Shri Balaji area.

Mineral phase (%)	SBL-1	SBL-2	SBL-3	SBL-4	SBL-5
Quartz	94.5	92.3	70.1	90.8	72.4
Mica	0.3	0.0	0.0	0.0	0.0
Albite	0.0	0.0	0.0	0.0	0.0
Microcline	3.8	0.0	5.9	5.9	7.4
Kaolinite	1.4	3.7	12.2	0.0	12.9
Illite	0.0	3.2	9.2	2.9	5.9
Smectite	0.0	0.0	0.0	0.3	0.3
Clinocllore	0.0	0.0	0.0	0.0	0.0
Pyrite	0.0	0.0	0.0	0.0	0.0
Ilmenite	0.0	0.0	1.3	0.0	0.0
Hematite	0.0	0.8	1.3	0.0	1.1
Total silicates	98.6	92.3	76.0	96.7	79.8
Total clays	1.4	6.9	21.4	3.2	19.1

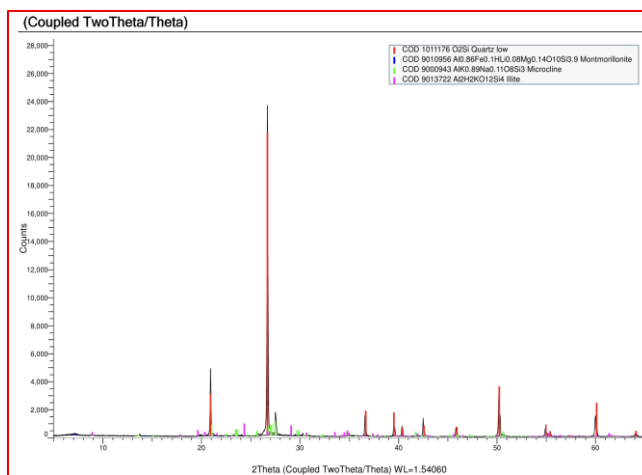
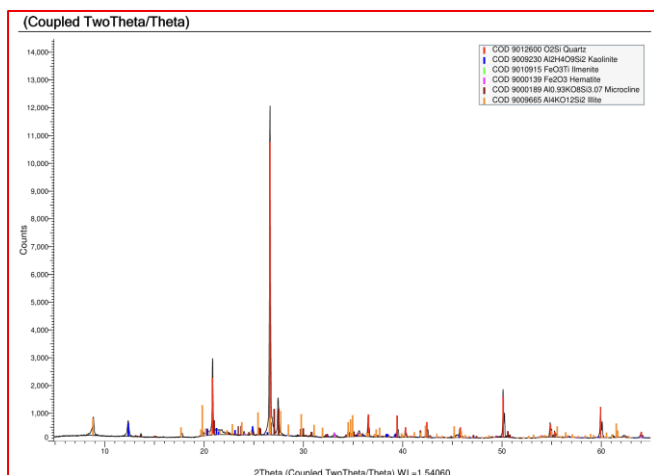
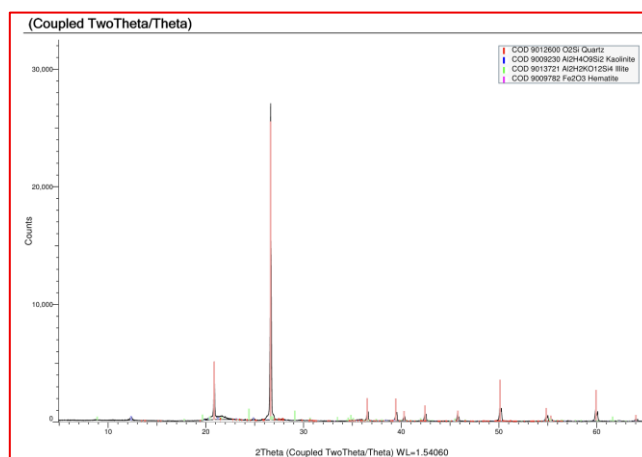
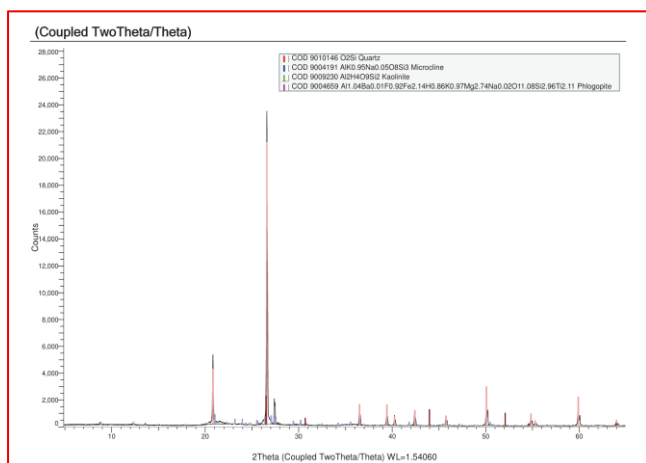


Fig. 3. Representative XRD diffractograms of the Nagaur sandstone samples (SBL-1 to SBL-4), showing dominant quartz reflections and subordinate microcline, kaolinite, illite, smectite, hematite, and ilmenite peaks were detected.

Major-Element Geochemistry

Whole-rock XRF analysis demonstrates a strongly silica-rich composition for all five analysed Nagaur Sandstone samples. The major-element concentrations are presented in Table 4. SiO_2 is the dominant oxide and ranges from 76.792 to 93.651 wt.%. SBL-2 records the highest SiO_2 concentration (93.651 wt.%), followed by SBL-4 (92.105 wt.%) and SBL-1 (91.642 wt.%). SBL-3 and SBL-5 contain comparatively lower SiO_2 concentrations of 80.771 and 76.792 wt.%, respectively. Al_2O_3 varies from 1.708 to 10.973 wt.%. The lowest concentration occurs in SBL-4, whereas SBL-5 contains the highest Al_2O_3 concentration. SBL-3 also contains relatively elevated Al_2O_3 (8.132 wt.%), while SBL-1 and SBL-2 contain lower concentrations of 3.652 and 3.379 wt.%, respectively. The higher Al_2O_3 concentrations in SBL-3 and SBL-5 are consistent with their comparatively greater clay-mineral contents identified by XRD. K_2O ranges from 0.263 to 3.308 wt.%. SBL-2 contains the lowest K_2O concentration, whereas SBL-5 records the highest value. SBL-3 also contains relatively elevated K_2O (2.819 wt.%). The higher K_2O contents correspond broadly with the occurrence of microcline and illite in these samples, although the bulk-rock concentration reflects the combined contribution of all K-bearing phases.

Fe_2O_3 concentrations range from 0.916 to 5.213 wt.%. SBL-2 records the lowest Fe_2O_3 content, whereas SBL-3 contains the highest concentration. SBL-5 also shows an elevated Fe_2O_3 concentration of 3.976 wt.%. The relatively high Fe_2O_3 contents of SBL-3 and SBL-5 correspond with the occurrence of iron-bearing phases in the XRD data and ferruginous material observed during petrographic examination. CaO remains relatively low throughout the analysed sample set, ranging from 0.461 to 0.698 wt.%. MgO ranges from below the reported detection level in SBL-1 and SBL-2 to 2.498 wt.% in SBL-5. TiO_2 varies from 0.221 to 0.950 wt.%, with the highest value occurring in SBL-5. P_2O_5 shows comparatively limited variation, ranging from approximately 0.647 to 0.673 wt.%. The major-element data therefore demonstrate substantial compositional variability despite the consistently quartz-rich character of the sandstone. Samples SBL-1, SBL-2, and SBL-4 are distinguished by very high SiO_2 and comparatively low Al_2O_3 , whereas SBL-3 and SBL-5 contain relatively lower SiO_2 and higher Al_2O_3 , Fe_2O_3 , and K_2O . These variations correspond broadly with differences in feldspar and clay-mineral abundance identified by petrographic and XRD analyses.

Table 4. Major-element composition of the Nagaur Sandstone samples determined by XRF

Oxide (wt.%)	SBL-1	SBL-2	SBL-3	SBL-4	SBL-5
SiO_2	91.642	93.651	80.771	92.105	76.792
Al_2O_3	3.652	3.379	8.132	1.708	10.973
Fe_2O_3	1.534	0.916	5.213	1.867	3.976
K_2O	1.547	0.263	2.819	1.966	3.308
CaO	0.577	0.698	0.461	0.684	0.528
MgO	0.000	0.000	1.235	0.625	2.498
TiO_2	0.221	0.254	0.466	0.223	0.950
P_2O_5	0.668	0.667	0.647	0.670	0.673

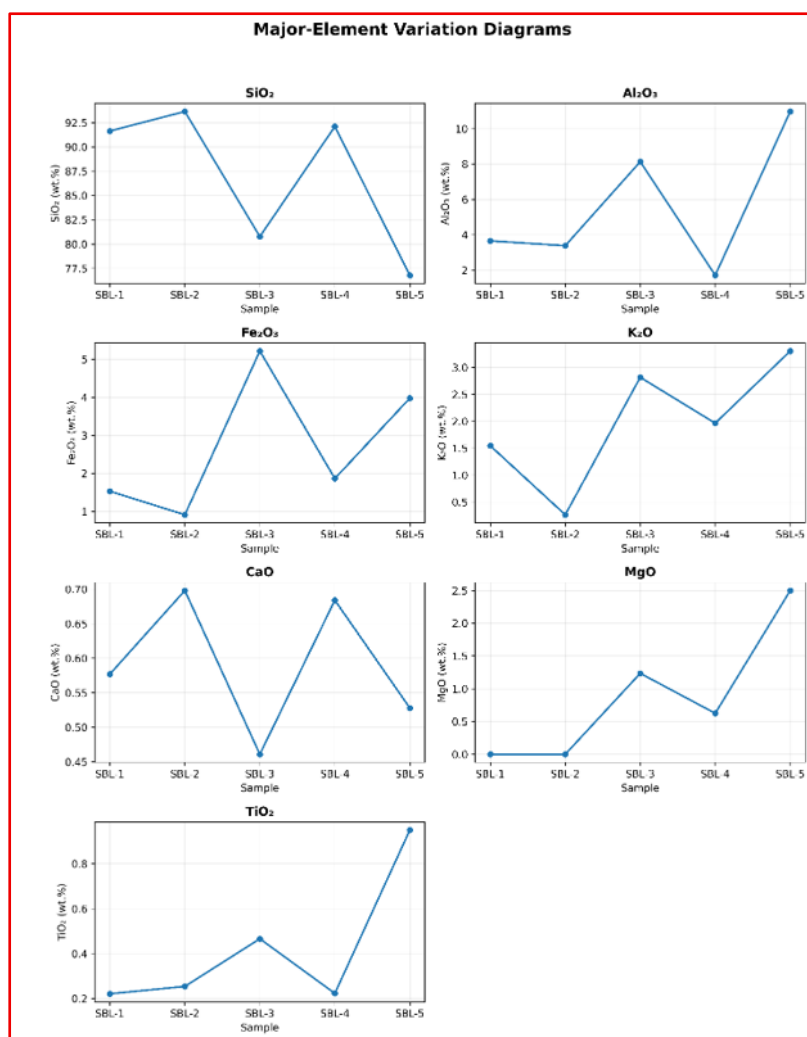


Fig. 4 presents the major-element variation diagrams for the analysed sandstone samples.

Integrated Mineralogical and Geochemical Variability

The combined petrographic, XRD, and XRF results reveal systematic relationships between framework composition, mineral assemblages, and bulk-rock chemistry within the studied Nagaur Sandstones. The samples with the highest quartz contents generally display lower Al₂O₃ and relatively low concentrations of clay minerals. SBL-1, for example, contains 94.5% quartz by XRD, only 1.4% total clay minerals, and 91.642 wt.% SiO₂. Similarly, SBL-2 contains 92.3% quartz, 6.9% total clay minerals, and the highest SiO₂ concentration of 93.651 wt.%.

In contrast, SBL-3 and SBL-5 contain substantially lower quartz proportions and higher clay-mineral abundances. SBL-3 contains 70.1% quartz and 21.4% total clay minerals, accompanied by 8.132 wt.% Al₂O₃, 5.213 wt.% Fe₂O₃, and 2.819 wt.% K₂O. SBL-5 contains 72.4% quartz and 19.1% total clay minerals, together with 10.973 wt.% Al₂O₃, 3.976 wt.% Fe₂O₃, and 3.308 wt.% K₂O. These associations indicate that the lower-silica samples contain greater contributions from clay minerals, feldspar, and iron-bearing phases.

The relationship between K₂O and mineralogy is particularly evident in SBL-3 and SBL-5, where elevated K₂O corresponds with the occurrence of microcline and illite. This relationship indicates that K-bearing minerals make a measurable contribution to the bulk chemical composition. However, the available dataset does not permit separation of the individual contributions of microcline, illite, and other potential K-bearing components.

The Fe₂O₃-rich character of SBL-3 and SBL-5 is likewise consistent with the occurrence of hematite and ferruginous material. The presence of these iron-bearing phases demonstrates mineralogical variability

within the sandstone succession, but does not by itself establish whether the phases are predominantly detrital, authigenic, or diagenetic.

Taken together, the analytical results demonstrate that the Nagaur Sandstones are characterized by a **quartz-dominated but compositionally heterogeneous framework**, with variations in feldspar, clay minerals, iron-bearing phases, and associated major-element concentrations. These relationships provide the principal empirical basis for the provenance and mineralogical-alteration interpretations developed in Section 5.

SUMMARY OF RESULTS

The integrated analytical results establish four principal characteristics of the Nagaur Sandstones from the Shri Balaji area. First, petrographic analysis demonstrates a **quartz-dominated framework with subordinate microcline and minor plagioclase**, accompanied by variable ferruginous and argillaceous material. Second, the Q–F–L modal data show that quartz constitutes approximately **70–94%** of the framework grains, whereas feldspar contributes approximately **6–30%**, with negligible lithic-fragment contribution. Third, XRD analysis confirms quartz as the dominant mineral phase and identifies variable proportions of microcline, kaolinite, illite, and minor iron-bearing phases. Finally, XRF analysis demonstrates a strongly silica-rich bulk composition, with SiO₂ ranging from **76.792 to 93.651 wt.%,** accompanied by systematic variations in Al₂O₃, Fe₂O₃, K₂O, MgO, CaO, P₂O₅, and TiO₂.

The close correspondence between petrographic, mineralogical, and geochemical variations indicates that the studied sandstones are compositionally heterogeneous despite their overall quartz-rich character. The observed relationships provide a basis for evaluating the nature of their source rocks, sedimentary modification, mineralogical alteration, and post-depositional evolution in the following discussion.

DISCUSSION

The provenance and post-depositional history of the Nagaur Sandstones at Shri Balaji can be evaluated effectively through the integrated interpretation of their framework-grain composition, bulk mineralogy, and whole-rock major-element geochemistry. The sandstone composition represents the combined influence of source-rock characteristics, sediment transport and hydraulic sorting, recycling, chemical alteration, and subsequent diagenetic modification. Consequently, individual petrographic, mineralogical, or geochemical parameters should not be considered independently when reconstructing provenance or source-area alteration. In the present study, the combined Q–F–L modal composition, XRD mineral assemblages, and XRF major-element chemistry provide mutually complementary constraints on the composition and evolution of the sedimentary detritus.

Provenance of the Nagaur Sandstones

The petrographic composition of the Shri Balaji Nagaur Sandstones provides the primary constraint on their provenance. The framework assemblage is strongly dominated by quartz, accompanied by subordinate feldspar and negligible lithic fragments. Quartz grains are predominantly monocrystalline and display non-undulatory to weakly undulatory extinction, whereas feldspar grains are locally preserved and include microcline with subordinate plagioclase. The coexistence of abundant quartz and feldspar is characteristic of sediment derived from quartz- and feldspar-bearing crystalline source rocks and is compatible with felsic igneous and metamorphic source lithologies. However, this mineral assemblage is not diagnostic of a single source province and may occur in several Precambrian continental terranes.

The modal Q–F–L data provide further support for a quartz–feldspar-dominated provenance. The analysed samples from SBL-1 to SBL-10 contain approximately 70.1–93.7% quartz and 6.3–29.9% feldspar, whereas lithic fragments were not recorded in the point-count dataset. The absence of significant lithic components, together with the high abundance of quartz, indicates a compositionally mature to sub-mature detrital assemblage. The particularly high quartz proportions in samples such as SBL-2 and SBL-8 may reflect prolonged sediment transport and/or recycling, whereas the relatively higher feldspar contents in SBL-3 and SBL-5 indicate greater preservation of less resistant framework minerals.

The Q–F–L distribution therefore suggests that the sandstone composition was not completely uniform during deposition. Variations in the relative abundance of quartz and feldspar may reflect changes in sediment supply, differential hydraulic sorting, variable degrees of sedimentary recycling, or spatial differences in source contribution. Importantly, the Q–F–L framework does not permit a unique identification of the source terrain because similar quartz–feldspar-rich compositions can be generated from different continental basement settings (Dickinson et al., 1983).

The XRD results reinforce the petrographic interpretation. Quartz is the dominant mineral phase in all five analysed samples, ranging from 70.1 to 94.5%, while microcline occurs in variable proportions of up to 7.4%. The preservation of microcline is particularly relevant because feldspar is generally more susceptible to chemical alteration than quartz. Its occurrence, together with the relatively high quartz abundance, indicates that a significant proportion of the original crystalline detrital framework was preserved during sediment generation and subsequent deposition. The variable abundance of microcline among the samples may additionally reflect differences in source composition and/or selective destruction of feldspar during weathering and transport.

The whole-rock XRF data are consistent with this mineralogical framework. The sandstone samples contain very high SiO₂ concentrations of 76.79–93.65 wt.%, reflecting the dominant contribution of quartz. In contrast, samples with relatively greater clay and feldspar contents show higher concentrations of Al₂O₃ and K₂O. For example, SBL-3 and SBL-5 contain comparatively high Al₂O₃ concentrations of 8.13 and 10.97 wt.%, respectively, together with K₂O values of 2.82 and 3.31 wt.%. These compositions correspond broadly with the greater abundance of clay minerals and feldspar identified by XRD. The relationship between mineralogical and chemical composition therefore suggests that much of the observed geochemical variability is controlled by differences in the proportions of quartz, feldspar, and clay-rich components.

Within the regional geological framework, the surrounding Precambrian continental crust provides several plausible source components capable of supplying quartz- and feldspar-rich detritus. Regional provenance investigations of the Marwar Supergroup have demonstrated temporal and spatial variations in sediment sources and have identified contributions from different Precambrian geological domains (George and Ray, 2017). The present petrographic and geochemical dataset is compatible with derivation from a heterogeneous quartz–feldspar-bearing Precambrian continental source region, including felsic igneous and metamorphic lithologies. However, the available data do not provide sufficient evidence to assign the Shri Balaji sandstones exclusively to the Malani Igneous Suite, Aravalli–Delhi domains, BGC-II, or any other individual source terrane.

Thus, the most appropriate provenance interpretation from the present dataset is that the Nagaur Sandstones were derived predominantly from quartz- and feldspar-rich continental crystalline sources, with their final composition subsequently modified by sediment transport, hydraulic sorting, recycling, and mineralogical alteration.

Paleo-weathering and Chemical Alteration

The mineralogical and geochemical characteristics of the Nagaur Sandstones also provide evidence for variable chemical alteration of the detrital material. However, the available dataset should be interpreted cautiously because the present XRF analyses do not include reliably quantified Na₂O, and therefore conventional Na-dependent quantitative weathering indices cannot be independently constrained. Accordingly, the present discussion focuses on the qualitative mineralogical and geochemical indicators of alteration rather than assigning numerical weathering intensities or specific paleoclimatic conditions.

The preservation of feldspar, particularly microcline, indicates that chemical alteration of the detrital framework was not complete prior to deposition. Microcline occurs in several of the analysed samples, with the highest XRD abundance recorded in SBL-5 (7.4%), while SBL-3 and SBL-5 also contain substantial clay-mineral components. This coexistence of preserved feldspar and secondary or fine-grained clay phases indicates that the sediment experienced variable degrees of mineralogical modification rather than a uniform alteration history.

The XRD data reveal considerable variation in clay-mineral abundance. Total clay minerals range from only 1.4% in SBL-1 to 21.4% in SBL-3, with SBL-5 containing approximately 19.1%. Kaolinite reaches 12.2% in SBL-3 and 12.9% in SBL-5, whereas illite reaches 9.2% in SBL-3 and 5.9% in SBL-5. Minor smectite occurs in SBL-4 and SBL-5. These variations demonstrate substantial differences in the fine-grained mineral fraction between samples.

The occurrence of kaolinite may be associated with alteration of feldspar-bearing detritus, whereas illite may represent either detrital clay input or subsequent mineralogical modification. Because bulk XRD analysis alone does not establish the precise paragenetic origin of individual clay minerals, these phases should not be interpreted exclusively as products of pre-depositional weathering. Some clay minerals may have formed or been modified during burial and diagenesis. The observed clay-mineral assemblage therefore represents a potentially composite signal involving source-area alteration, sediment transport, and post-depositional mineralogical transformation.

The major-element data provide additional evidence for compositional variability related to the relative abundance of feldspar and clay-rich components. Samples SBL-3 and SBL-5, which contain relatively high clay-mineral proportions, also show elevated Al_2O_3 concentrations of 8.13 and 10.97 wt.%, respectively. Their relatively high K_2O contents of 2.82 and 3.31 wt.% are consistent with the presence of K-bearing minerals, particularly microcline and illite. Conversely, quartz-rich samples such as SBL-1 and SBL-2 contain very high SiO_2 and comparatively low Al_2O_3 contents.

Fe_2O_3 also varies among the samples, reaching 5.21 wt.% in SBL-3. XRD identification of hematite in SBL-2, SBL-3, and SBL-5, together with the presence of ferruginous material observed petrographically, indicates that iron-bearing phases contribute to the bulk chemical variability. The occurrence of minor ilmenite in SBL-3 provides an additional source of Fe and Ti. These iron-bearing phases indicate that oxidation-related mineralogical components are present, although the available petrographic data do not establish the precise timing of their formation.

Overall, the combined mineralogical and geochemical evidence indicates heterogeneous chemical alteration of the source-derived detritus, superimposed by physical sorting and subsequent diagenetic modification. The preservation of feldspar together with variable kaolinite and illite abundance suggests that alteration was spatially and/or compositionally heterogeneous. Importantly, the present dataset does not independently establish a specific warm-humid, semi-arid, or arid paleoclimate. A robust reconstruction of source-area paleoclimate would require additional provenance-sensitive and weathering-sensitive datasets.

Depositional Environment and Tectonic Implications

The provenance and alteration characteristics of the Shri Balaji Nagaur Sandstones should be considered within the broader stratigraphic evolution of the Marwar Supergroup. The succession records a transition from siliciclastic sedimentation in the Jodhpur Group to carbonate-dominated deposition in the Bilara Group, followed by renewed siliciclastic sedimentation within the Nagaur Group. The studied sandstone succession therefore represents part of a broader change in sediment supply and depositional conditions during the later evolution of the Marwar Basin (GSI, 2001; George and Ray, 2017).

At Shri Balaji, the investigated sandstone beds occur within the Nagaur succession and display considerable variation in colour, grain size, sorting, and association with argillaceous horizons. The occurrence of bedded sandstone, locally associated with shale or argillaceous material, together with variations from quartz-rich to relatively feldspar-rich compositions, indicates fluctuations in sediment composition and depositional conditions. These variations may reflect changes in sediment discharge, source contribution, hydraulic sorting, and local depositional processes.

The high quartz content of many samples indicates substantial compositional maturity of the deposited sediment. However, the preservation of appreciable feldspar in several samples demonstrates that the succession also contains relatively less altered detrital components. Such variation can result from changes

in sediment transport distance, source-rock exposure, sediment recycling, or the relative contribution of different source lithologies.

From a tectonic perspective, the data are compatible with sediment generation from the heterogeneous Precambrian continental framework surrounding the Marwar Basin. The dominance of quartz and feldspar and the absence of abundant volcanic or metamorphic lithic fragments do not provide evidence for a single distinctive tectonic provenance. Rather, the composition is consistent with sediment supply from exposed crystalline continental source regions, followed by modification during transport and deposition.

The stratigraphic transition from the Bilara carbonate succession to the overlying Nagaur siliciclastic succession represents an important change in the nature of sediment supply to the basin. The present data demonstrate that the Nagaur Sandstones contain substantial terrigenous quartz–feldspar detritus, indicating renewed siliciclastic input during deposition of the Nagaur succession. However, the available petrographic and geochemical evidence is insufficient to establish a specific tectonic mechanism responsible for this change.

Similarly, the present dataset does not permit definitive assignment of the Shri Balaji sandstone to a particular depositional sub-environment such as fluvial, tidal, shoreface, deltaic, or coastal settings. Such interpretations would require integration with detailed sedimentary-structure analysis, palaeocurrent measurements, facies architecture, grain-size distributions, and stratigraphic relationships. The present study therefore restricts its interpretation to the provenance and compositional evolution of the sandstone rather than assigning a specific depositional sub-environment.

Integrated Provenance–Weathering Model

The combined petrographic, XRD, and XRF results indicate that the Nagaur Sandstones at Shri Balaji preserve a composite provenance–alteration signal rather than a simple record of a single source or process. The first-order control is provided by the quartz-rich framework and subordinate feldspar assemblage, which indicate derivation predominantly from quartz- and feldspar-bearing continental crystalline rocks. The Q–F–L data demonstrate strong quartz–feldspar dominance across the investigated samples, while the absence of significant lithic fragments suggests that the detrital assemblage was either derived largely from crystalline source rocks or was substantially modified through sedimentary recycling and selective preservation. The very high SiO₂ concentrations observed in the XRF dataset independently support the quartz-rich nature of the sandstone.

A second component of the signal is represented by the variable clay-mineral assemblage. The occurrence of kaolinite, illite, and minor smectite, together with variable feldspar preservation, demonstrates that the sandstone underwent differential mineralogical alteration. The contrasting mineralogical compositions of SBL-1 and SBL-2 relative to SBL-3 and SBL-5 are particularly significant. The former samples are strongly quartz-rich and clay-poor, whereas the latter contain greater clay abundances and relatively elevated Al₂O₃, Fe₂O₃, and K₂O concentrations. These variations indicate that the bulk composition of the sandstone was influenced by several interacting processes. Source-rock heterogeneity controlled the initial mineralogical composition; chemical alteration modified susceptible minerals such as feldspar; hydraulic sorting and sedimentary recycling enhanced the relative abundance of resistant quartz; and post-depositional mineralogical modification contributed to the development or redistribution of clay and iron-bearing phases.

Accordingly, the Shri Balaji Nagaur Sandstones are best interpreted as the product of a multi-stage provenance-sediment modification system, involving heterogeneous Precambrian crystalline sources, variable source-area alteration, sediment transport and sorting, selective preservation and recycling of resistant minerals, and subsequent diagenetic modification. The present data support a broad continental crystalline provenance but do not permit exclusive attribution to a single Precambrian terrane. A more precise reconstruction of individual source terrains and the relative contributions of source-area weathering versus sedimentary and diagenetic processes would require additional provenance-sensitive datasets. In particular, trace-element and rare-earth-element geochemistry, reliable complete major-element analyses

including Na_2O , detrital zircon U–Pb geochronology, and Nd isotopic data would provide stronger constraints on source terranes and sediment pathways.

DISCUSSION

The integrated evidence therefore indicates that the Nagaur Sandstones of the Shri Balaji area represent quartz-rich, feldspar-bearing siliciclastic sediments derived predominantly from heterogeneous Precambrian continental crystalline sources. Their present mineralogical and geochemical composition reflects not only source-rock characteristics but also variable alteration, sedimentary sorting and recycling, and post-depositional modification. The available evidence supports interpretation of **heterogeneous provenance and variable chemical alteration**, but it does not justify assignment of a unique source terrane or a specific paleoclimatic regime. This integrated interpretation provides a more robust framework for understanding the provenance and sedimentary evolution of the Nagaur succession within the Marwar Supergroup.

CONCLUSIONS

The present study integrates petrography, modal framework-grain analysis, X-ray diffraction (XRD), and whole-rock X-ray fluorescence (XRF) geochemistry to investigate the provenance and mineralogical alteration of the Nagaur Sandstones exposed at the Shri Balaji area, Nagaur District, Rajasthan. The principal conclusions derived from the integrated dataset are as follows:

Quartz-Dominated Framework Composition

The Nagaur Sandstones are characterized by a strongly quartz-dominated framework with subordinate feldspar and negligible lithic fragments. Modal Q–F–L analysis of samples SBL-1 to SBL-10 shows quartz contents of 70.1–93.7% and feldspar contents of 6.3–29.9%, with no lithic fragments recorded in the analysed framework population. This composition indicates a mature to sub-mature siliciclastic assemblage dominated by resistant quartz and feldspar-bearing detritus.

Continental Crystalline Provenance

The combined petrographic, Q–F–L, XRD, and XRF evidence indicates derivation predominantly from quartz- and feldspar-bearing continental crystalline source rocks, including felsic igneous and metamorphic lithologies. The preservation of microcline and minor plagioclase, together with very high SiO_2 concentrations, supports this interpretation. However, the available dataset does not permit exclusive attribution of the Nagaur Sandstones to a single Precambrian source terrane such as the Malani, Aravalli–Delhi, BGC-II, or another specific geological domain.

Strong Silica Enrichment

Whole-rock XRF analysis demonstrates a strongly silica-rich composition, with SiO_2 ranging from 76.79 to 93.65 wt.%. Variations in Al_2O_3 , Fe_2O_3 , K_2O , MgO , CaO , P_2O_5 , and TiO_2 reflect differences in the relative abundance of feldspar, clay minerals, quartz, and minor Fe–Ti-bearing phases among the analysed samples.

Variable Mineralogical Alteration

XRD analysis confirms quartz as the dominant mineral phase and identifies variable amounts of microcline, kaolinite, illite, and minor smectite, hematite, and ilmenite. Total clay-mineral contents vary considerably between samples, reaching 21.4% in SBL-3 and 19.1% in SBL-5. The coexistence of preserved feldspar and variable clay-mineral assemblages indicates heterogeneous chemical alteration of source-derived detritus, rather than a uniform alteration history.

Influence of Sedimentary and Post-Depositional Processes

The contrasting mineralogical and chemical compositions of individual samples indicate that the present

sandstone composition cannot be attributed solely to source-rock characteristics. Hydraulic sorting, sedimentary recycling, selective preservation of resistant minerals, and post-depositional mineralogical modification have likely contributed to the observed variability. The occurrence of hematite, ilmenite, clay minerals, and ferruginous or argillaceous material further demonstrates mineralogical modification of the original detrital assemblage.

Implications for the Evolution of the Nagaur Succession

The quartz–feldspar-rich terrigenous composition of the investigated sandstone records substantial siliciclastic sediment supply during deposition of the Nagaur succession following the carbonate-dominated Bilara phase. The observed compositional variability indicates changes in sediment supply and/or sediment modification during deposition. However, the available dataset does not permit definitive assignment of the studied succession to a single depositional sub-environment such as fluvial, tidal, shoreface, or deltaic.

Paleoweathering Interpretation

The integrated petrographic and mineralogical evidence supports the presence of variable chemical alteration within the source-derived detritus, as indicated by the coexistence of feldspar, kaolinite, illite, and other alteration-related phases. However, because reliable Na₂O data are unavailable from the present XRF dataset, the study does not attempt to quantify weathering intensity using Na-dependent geochemical indices or to infer a specific paleoclimatic regime.

Integrated Provenance–Alteration Model

Overall, the Nagaur Sandstones at Shri Balaji preserve a composite geological signal produced by the interaction of heterogeneous Precambrian provenance, variable source-area alteration, sediment transport and hydraulic sorting, sedimentary recycling, and subsequent diagenetic modification. The integrated petrographic–XRD–XRF approach therefore provides a robust framework for distinguishing source-controlled mineralogical characteristics from later sedimentary and post-depositional modifications.

Future Provenance Constraints

More precise identification of individual source terranes and reconstruction of sediment pathways will require additional provenance-sensitive datasets, particularly trace-element and rare-earth-element geochemistry, complete major-element analyses including reliable Na₂O measurements, detrital-zircon U–Pb geochronology, and Nd isotopic compositions.

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